Active plasmonics: Controlling signals in Au/Ga waveguide using nanoscale structural transformations

A. V. Krasavin[a] and N. I. Zheludev
School of Physics and Astronomy, University of Southampton, SO17 1BJ, United Kingdom

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We have developed a concept for active plasmonics that exploits nanoscale structural transformations which is supported by rigorous numerical analysis. We show that surface plasmon-polariton signals in a metal-on-dielectric waveguide, containing a gallium section a few microns long, can be effectively controlled by switching the structural phase of gallium. The switching may be achieved by either changing the waveguide temperature or by external optical excitation. The signal modulation depth could exceed 80% and switching times are expected to be in the picosecond–microsecond time scale. © *2004 American Institute of Physics.*
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We are entering the age of integrated photonic devices for signal and information processing when planar waveguides and photonic crystal structures are being intensively investigated as primary solutions for guiding light in such devices. There may, however, be another means of making highly integrated optical devices, with structural elements smaller than the wavelength, enabling strong guidance and manipulation of light using metallic and metallodielectric nanostructures. Here, plasmon-polariton waves, i.e., optical excitations coupled with collective electronic excitations, are used as information carriers. A range of very promising nanostructures that guide plasmon-polariton waves[1–3] are currently being investigated. Surface plasmon polaritons in gold films can propagate for tens of microns and may be guided by structuring the metal film and creating polaritonic band-gap materials.[4] Propagating plasmon-polariton excitations in nanostructured metal films are, therefore, clearly emerging as an information carrier for highly-integrated photonic devices.[5] However, we will only be able to speak about ''plasmonics'' in the same way we speak about ''photonics'' when efficient techniques for active manipulation of surface polariton-polariton (SPP) signals are identified.

Here, we propose a concept of active nanoscale functional elements operating with SPP signals. Our approach takes advantage of the most characteristic features of SPPs, namely that their propagation depends strongly on the properties of the metal in a thin layer near the surface. These features are exploited by combining them with the recently developed concept of achieving nanoscale photonic functionality using structural phase transitions in polyvalent metals, an idea which has already been shown to offer all optical switching at milliwatt power levels in thin films[6] and nanoparticles,[7] and promises another type of photodetector.[8] Here, we show that SPP signals in metallic on dielectric waveguides containing a gallium section a few microns long can be effectively controlled by switching the crystalline gallium section of the waveguide from one structural phase to another. The switching may be achieved by both changing the waveguide temperature and by external optical excitation. Metallic gallium is a uniquely suitable material for this application. It is known for its polymorphism.[9] In α-gallium, the stable ''ground-state'' phase[10] molecular and metallic properties coexist—some interatomic bonds are strong covalent bonds which form well-defined Ga_2 dimers (molecules), and the rest are metallic bonds. The structure is highly anisotropic, with much better thermal and electrical conductivity in the ''metallic planes'' than along the covalent bonds. Remarkably, α-gallium has a very low melting point, 29.8 °C. The covalent bonding leads to a strong optical absorption peak centered at 2.3 eV and spreading from approximately 0.68 eV ($\sim$310 nm) to the midinfrared part of the spectrum. Optical properties of the α-Ga and more metallic phases, metastable at normal conditions, are greatly different; in terms of the dielectric coefficients of liquid and solid gallium, they are huge. At a wavelength of 1.55 μm, we have $|\varepsilon_{\text{liquid}}|/|\varepsilon_{\alpha}| \sim 7$. The metallic metastable phase (quasi-melt) may be achieved by simple heating, or by light absorption through a nonthermal ''optical melting'' mechanism via destabilization of the optically excited covalent bonding structure.[6] Whatever the mechanism of phase transition, it is a surface-mediated effect and develops as propagation of the metallic phase from the surface into the bulk of the semiconductorlike α-phase. As the phase transition only involves a few tens of atomic layers of gallium at the interface, it is highly reproducible and fully reversible and could run for millions of cycles without noticeable changes. High-quality gallium interfaces with silica may be achieved using various techniques, from squeezing molten gallium to ultrafast pulsed laser deposition.[11]

To evaluate the potential switching characteristics of the SPP waveguide, we numerically modeled it using the finite element method. We investigated a gold film waveguide containing a gallium section of length L on a silica substrate. To model coupling and decoupling of optical radiation to and from the waveguide, two ten element gratings were placed at both ends of the structure (Fig. 1). Although optimization of coupling efficiency was not the prime objective of this study, we found that with a rectangular coupling grating conversion

[a]Electronic mail: avk@soton.ac.uk

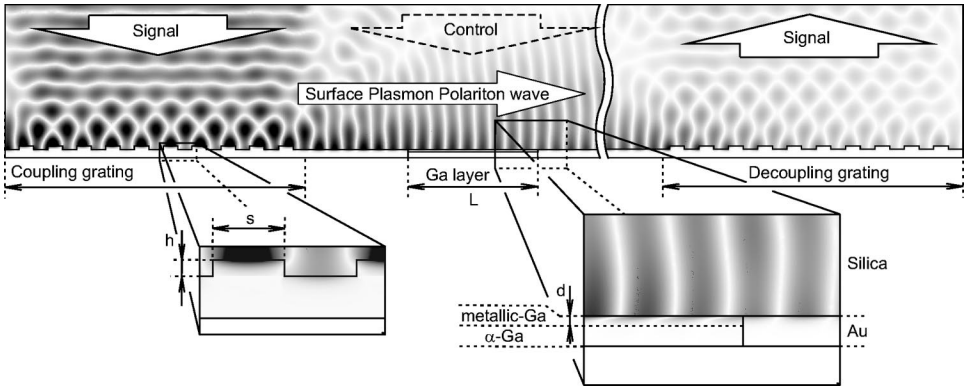

FIG. 1. A SPP gold-on-silica waveguide containing a gallium switching section. The metallic film is at the bottom of the silica substrate. Field mapping shows the magnitude of the z component of the magnetic field.

efficiencies in excess of 20% into each of the SPP waves propagating in opposite directions away from the grating could be achieved for $s/h \approx 1/5$, and a grating period $2s$ close to the wavelength of incident light. Coupling levels above 30% are possible with gratings of complex profile. In such a waveguide, the SPP wave propagates at the interface between the metal film and silica substrate, through the gold and gallium sections. SPP decay length in a continuous gold/silica waveguide is 53 μm for the excitation wavelength of 1.31 μm. In the waveguide containing a Ga section, the transmitted SPP wave attenuates due to the mismatch of dielectric characteristics at the Au–Ga border and losses which are much higher in gallium than in gold.

We modeled that the gallium section of the waveguide may be converted from the ground α-phase to the metallic liquidlike phase. We also modeled that this change could take place as interface metallization: A thin layer of metallic gallium of thickness d develops at the silica interface (see Fig. 1). As α-gallium is a highly anisotropic material (crystal class mmm), we performed calculations of the waveguide transmission (disregarding coupling–decoupling losses) for all main crystalline orientations of the Ga film at the interface in the range of optical excitation wavelengthes from 0.9μm to 2.0μm. Figure 2 shows the results of these calculations at different wavelengths of incident light for a waveguide containing a gallium section of length $L=2.5$ μm, assuming that the gallium section is a homogenously crystal of given orientations or is a fully molten isotropic liquid phase. The graph in Fig. 2 also shows the transmission levels calculated using an analytical theory which accounts for absorption in an isotropic infinite homogeneous waveguide[12] for three main values of the crystalline dielectric coefficient of Ga and for the dielectric properties of the liquid state. The following notation was used: Curve AB corresponds to the crystalline structure of Ga with its A axis lying in the interface plane perpendicular to the direction of the SPP propagation and its B axis perpendicular to the strip. A similar notation applies to curves BA/BC and CA/CB. The values of the complex dielectric coefficients of gallium and gold were taken from Refs. 13 and 14.

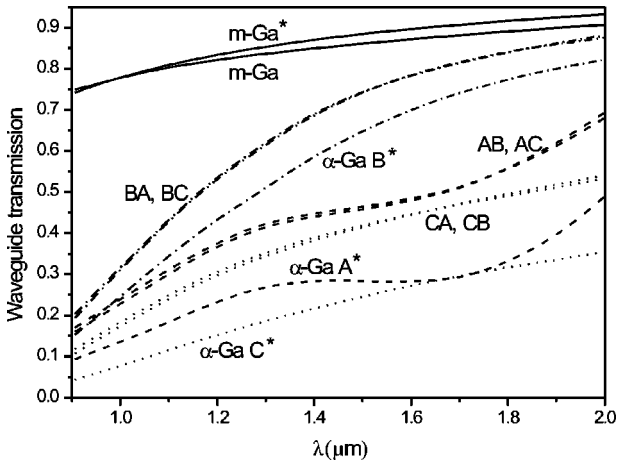

FIG. 2. Waveguide transmission as a function of wavelength for different phases and crystalline orientations of gallium film. Curves without asterisks are calculated in finite element method numerical simulation, while curves marked with asterisks are obtained analytically. Compare the waveguide transmissions for the gallium section in the metallic phase ($m-$Ga and $m-$Ga*, solid lines) and crystalline phases (dashed lines).

Although the results of numerical analysis and analytical calculations show similar spectral trends, the magnitudes of transmission coefficients are somewhat different for these two approaches. We argue that the discrepancy reflects limitations of the analytical theory which ignores the reflection of SPPs at the gold/gallium border. More importantly, however, the analytical theory also ignores the ''hopping'' of the electromagnetic wave across the narrow gallium strip followed by recoupling of the excitation into the SPP on the other side of the strip. These effects are very pronounced in numerical mapping of the fields and change the waveguide transmission in comparison with predictions of the analytical theory. Therefore, our calculations show that the waveguide transmission strongly depends on the structural phase of the gallium section and changing the phase could be used for actively controlling the transmission. As the structural transformation in gallium is a surface-mediated effect, two phases of gallium may coexist at the interface, with a thin layer of metallic phase sandwiched between silica and α-gallium. In fact, melting of gallium takes the form of ''surface melting'' with the molten phase thickness steadily increasing with temperature in a narrow temperature corridor just below the gallium bulk melting point. Similarly, light-induced metallization also develops as a surface-mediated effect and starts from the interface while the equilibrium thickness of the metallized layer d may be controlled by the light intensity. This gives a possibility of continuous ''analog'' control of

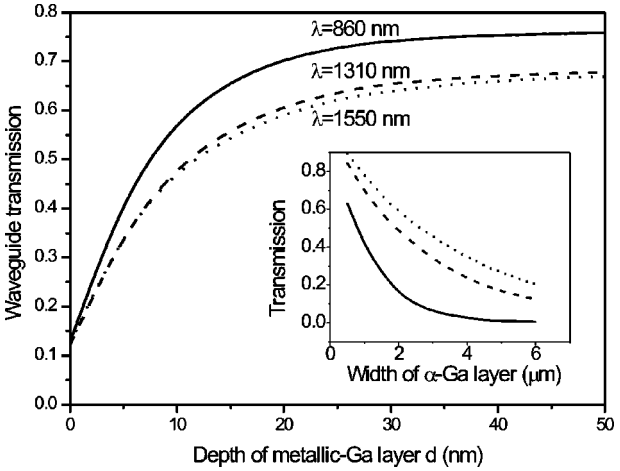

FIG. 3. Waveguide transmission as a function of the depth d of the metallic gallium layer. Length of the Ga section: 860 nm–2.2 μm, 1310 nm–5.8 μm, and 1550 nm–9 μm. Inset shows the dependence of transmission on the width L of gallium section.

the waveguide transmission. To analyze this effect, we calculated the waveguide transmission for different thicknesses of the metastable gallium phase up to $d=60$ nm for a number of incident wavelengths (see Fig. 3). For illustrative purposes, the gallium strip was taken to be polycrystalline α-gallium: Isotropic with dielectric constants averaged over crystal directions. In can be seen that the presence of the metallic liquid Ga layer, in the section of only a few microns long and depth of just $d=30$, nm can dramatically change the transmission of plasmons through the waveguide.

One, therefore, can envisage an active plasmonic device in which SPP transmission is controlled by the waveguide temperature in the range of a few degrees or external optical stimulation. In the near-infrared part of the spectrum, a typical fluence of optical excitation needed for converting the α-Ga phase to a metallic phase of several tens of nanometers deep is about 10 mJ/cm^2.[6] For a section of gallium waveguide 2.5 μm$\times$2.5 μm, the optical energy required for high-contrast switching would be in the order of 10 pJ. The envisaged application of the control light signal to the waveguide is schematically presented in Fig. 1 by a dashed arrow. When the excitation is terminated, the molten/metallic layer rapidly recrystallizes into the ground α-phase. The intrinsic switch-on time was measured for a gallium–silica interface, and was found to be 2–4 ps (Ref. 11), and we expect that the SPP switch-on time will also be in the scale of a few ps. We anticipate the SPP switch-off time to be in the microsecond–nanosecond time scales.[15] Notably, this is four to eight orders of magnitude faster than the currently achieved response time of optomechanical switching microdevices.

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